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GALILEO Li/SO_2 BATTERY MODULES

- PROGRAM UPDATE -

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ABSTRACT

In order to meet the unique power needs of NASA's Galileo Probe, the Li/SO_2 high rate "D" cells used in the battery modules have undergone some design changes, an upgrading of hardware quality requirements, and significant testing. A description of the design changes and the cell test data that are of a general nature is presented here. This data includes capacities, open circuit voltages, and internal resistance comparisons. A significant data base has been built up over the years and continues to grow.

INTRODUCTION

Honeywell Power Sources Center (HPSC) has been involved in the development of the Li/SO_2 Galileo Probe Battery with NASA and Hughes Aircraft Company (HAC) since 1978. This program has significantly broadened our experience and capabilities in design and manufacture of hardware to meet space requirements. The terms: performance, quality, and reliability, as regards Galileo high rate "D" cells, have taken on new meaning in this program. Due to the critical nature of this battery's performance, and the lack of previous flight experience with this system, a significant amount of testing has been done in this program. We feel the information gained from these tests has substantially improved the base of knowledge of Li/SO_2 cells and systems, and we would like to present these data for your information, evaluation, and possible use.

BACKGROUND

In a paper presented to this forum in 1982, Dr. L. S. Marcoux and Mr. B. P. Dagarin of Hughes Aircraft Company described the unique requirements for the NASA Galileo Probe power source and explained why the Li/SO_2 system was selected for the application over alternate electrochemistries. The savings in weight and volume were the overriding factors, but low temperature performance and shelf life were also important.

The basic power element, a module of thirteen high rate "D" cells in series, must provide energy after the Galileo probe leaves the orbiter. The requirements of a 150-day coast, seven hours of pre-entry, and approximately an hour of descent to the planet Jupiter, as well as test requirements, storage losses and contingency dictate a mission energy budget of 19.02 Ahrs for the three modules that comprise the Galileo Probe Battery.

Dr. Marcoux also discussed:

- Mission description and requirements,
- Battery system description,
- Battery safety considerations,
- Description of battery test program.

In a 1984 paper by HPSC and HAC, again at this forum, the test facilities developed and used during this program were discussed by Mr. W. T. Pertuch.

Today, I will present:

- Description of Cell Lots (Design Development),
- Cell Tests
    - Developmental
    - Storage/life tests
    - Environmental,
- Module Tests
    - Developmental
    - Environmental.

DESCRIPTION OF CELL LOTS

The Galileo Probe Battery flight hardware cells are from Lot 6. This cell lot has passed all acceptance criteria, and we have completed a preliminary buy-off of this hardware. Modules have been shipped to Hughes. Previous lots represent the technical evolution of the battery and demonstrate the intense quality assurance demanded for these batteries (See Table 1).

Lot 1 cells were used in:

- Baseline capacity tests
- Simulated battery tests.

Lot 2 cells were used in:

- Life tests
- Corrosion tests.

Alternate cells were used in:

- Baseline capacity tests
- Simulated battery tests
- Life tests
- Corrosion tests
- Vibration tests.

Lot 3 cells were used in:

- Corrosion tests
- Life tests
- Reversibility of Temperature Effect.

Lot 4 cells were used in:

- Cell qualification tests
- Module qualification tests
- Cell life tests.

Lot 5 cells were used in:

- Cell qualification tests
- Storage tests.

Lot 6 cells were used in:

- Cell qualification tests
- Module qualification tests
- Storage tests.

CELL TESTS

Early developmental cell tests indicated that the high rate "D" battery performance level was sufficient to meet the Galileo requirements, but they also showed that there was some design modifications and material and process upgrading required to meet the environmental requirements. Such areas included:

Cathode drying. - Reduced self-discharge reactions.

Increased anode tab widths. - Improved tolerance to vibration.

Grid added to anode. - Improved lithium utilization and added strength.

Lithium-Bromide concentration reduced. - Reduced corrosion.

Glass upgraded. - Reduced cell failure due to corrosion.

Electrolyte mixed in glass vessels. - Reduced contaminants.

Electrolyte reduction. - Increased ullage.

These improvements to the design and the manufacturing processes occurred as a result of data analyses from the extensive environmental, life, and corrosion testing performance on these cells and modules. Environmental tests include:

- o High Temperature Test
- o Sinusoidal Vibration Test
- o Random Vibration Test
- o 150-Day Coast Timer Test (accelerated and real time)
- o Entry Deceleration Test
- o Pressure Thermal Test
- o High Pressure and Condensing Moisture Test
- o Descent Load/Temperature Profile Test
- o DOT Safety Tests
- o Module Venting Test

Cell and modules have passed qualification and acceptance testing(1). The tests were very rigorous and simulated as closely as possible the predicted mission conditions.

While the environmental tests have expanded the baseline performance capabilities in general and specifically for use in space, that baseline is somewhat limited by the fact that it was geared to one specific scenario. The life, storage, and corrosion testing is more general in nature and, therefore, applicable in almost every facet of design where high rate "D" cells are used. I wish to emphasize this group of cell tests due to its universal nature. We obtained considerable data in the following tests:

- o Cell Real Time/Temperature Test -Lot 3
- o Cell Life Tests - Lots 3a, 4, 6
- o Cell Storage Test 0°C - Lot 5
- o Corrosion Tests - Alternate Cells

While I am including some capacity data on Lots 3 and 3a here in Table 2 and 3, I must remind you that this hardware was not to the final configuration, and we did run into corrosion problems with that design. Of much more value is the data from Lot 4, 5, and 6. Figures 1-8 address a comparison of data between Lot 4 and 6.

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(1) Lot 6 modules still must pass real time descent load/temperataure profile test.

This data includes:

- o Internal resistance (IR) versus time at 20°, 50°, 60°, and 70°,
- o OCV versus time at 20°, 50°, 60°, and 70°.

Figure 9 addresses Internal Resistance versus Capacity in Amp-hours.

As you will note, only limited data are available on Lot 6, but it appears that the lot 6 data follows Lot 4 data except where the chamber was shut down on the Lot 4 cells at 70°C.

Detailed analyses of Lot 4 and Lot 6 data would be premature at this point. This test extends out to the year 1990 and we expect valuable information will be gained by tracking results closely. Some general type trends might legitimately be gleaned now though,

- IR and OCV seem to indicate cell degradation at approximately the same time.
- An internal resistance reading greater than 1.50 ohms is an indication of cell failure.
- 70°C storage will limit life and may add risk to cell integrity.

This information with the additional data that will continue to be obtained will be of significant value in expanding our use of Li/SO_2 cells in future applications especially with what might be called these "pedigreed cells".

MODULE TESTING

The Galileo Probe Module has now passed all environmental test requirements which include:

- Sinusoidal Vibration - See Table 4
- Random Vibration - See Table 5
- Deceleration and Spin -See Table 6
- Temperature/Pressure - See Table 7 and Figure 10

Battery (three modules) capacity is measured on sets of hardware that have experienced accelerated and real time 150-day coast tests. To date, we have completed both Lot 4 discharge tests and the Lot 6 accelerated coast time discharge test. All discharge tests are conducted per the projected mission requirements for pre-entry (approximately 6 hours) and entry (approximately 1+ hours) time. The data are as follows:

	Lot 4	Lot 6
Accelerated Battery Test	23.9 Ah	23.3 Ah
Real Time Battery Test	21.6 Ah	Nov. 1985 test data

The slight reduction in Lot 6 capacity can be directly attributed to the reduction in cell electrolyte for Lot 6 cells as compared to Lot 4 cells. We also expect a like reduction in real time capacity for Lot 6.

SUMMARY

The test data we have obtained during the Galileo Program has provided us a baseline for further development of power sources for space, both in design and manufacturing processes. The data base gained from this effort for Li/SO_2 cells is not only significant in quantity but due to the quality built in these cells, we hope to be able to deduct new information and hopefully formulate new theories. Limited design variations and tight standard deviations on design characteristics may help define phenomenon previously not understood. Even more valuable will be the review of the relationship between acceptance criteria and the actual battery requirements during the flight to Jupiter. The profusion of applications for power sources in space will be greatly serviced by this program, and we plan to continue our analyses of all data (present and future) to help us meet those needs.

ACKNOWLEDGEMENTS

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The author would like to thank Dr. L. S. Marcoux, Mr. B. P. Dagarin, and Mr. R. Taenaka from HAC for their assistance in testing, organizing, and analyzing the test data during this program; Dr. S. Levy of Sandia National Laboratories for his technical advice; and Mr. J. Van Ess from NASA for his inputs to data analyses. The author would also like to acknowledge the significant support of NASA to the Galileo battery program.

TABLE 1. GALILEO Li/SO_2 CELL EVOLUTION

	Cathode	Anode		GTM		Electrolyte	
Designation	Cathode Drying	Grid	Tab, In.	Glass	Glass Protector	Process	LiBr Conc, %
Lot 1	No	No	0.2	Blue*	Yes	Metal No premix	8
Lot 2	No	No	0.2	Blue*	Yes	Metal No premix	8
Alternate Cells	Yes	Yes	0.2	Fusite 108	No	Glass premix	6.4
Lot 3 Lot 3a	Yes	Yes	0.6	Fusite 108	No	Glass premix	6.4
Lot 4	Yes	Yes	0.6	TA-23 Mo pin	No	Glass premix	6.4
Lot 5	Yes	Yes	0.6	TA-23 Mo pin	No	Glass premix Reduced Electrolyte	6.4
Lot 6	Yes	Yes	0.6	TA-23 Mo pin	No	Glass premix Reduced Electrolyte	6.4

*Glass Seal Products Glass No. 0054-3224

TABLE 2. LOT 3 REAL TIME/TEMPERATURE CAPACITY

Inverted Storage Time (yr.)	Temp. (°C)	Capacity (A-hrs)
0.000	0	5.67
.500	0	5.53
1.417	0	5.66
1.667	30	5.52
1.917	30	5.67
2.167	30	5.67
2.417	30 - 20	5.78
2.713	20	5.57
2.930	20	5.49
3.185	20	5.56
3.407	20	5.57
3.665	20	5.76

TABLE 3. LOT 3a LIFE TEST

Storage Temp. (^{o}C)	Inverted Storage Time							
	6 mos.	12 mos.	18 mos.	24 mos.	27 mos.	30 mos.	33 mos.	36 mos.
10	5.46	5.87	5.78	5.92	5.71	5.77	5.86	5.88
20	5.77	5.54	5.67	5.70	5.48	5.52	5.67	5.58
30	5.43	5.61	5.54	5.51	5.43	5.33	5.46	5.44
40	5.42	5.23	5.35	5.11	4.97	5.12	5.48	5.32
50	5.24	5.52	5.21	4.93[a]	--[a]	--[a]	--[b]	--

Baseline (from fresh cells): 5.80 Ahrs.
Average Capacity in Ahrs to 2.0V cutoff
Discharge Load: 4 amperes constant at $0^{o}C$

(a) Cell or cells incapable of sustaining 4-ampere load.
(b) $50^{o}C$-stored cells removed from test plan after 31 months per Hughes Aircraft Company

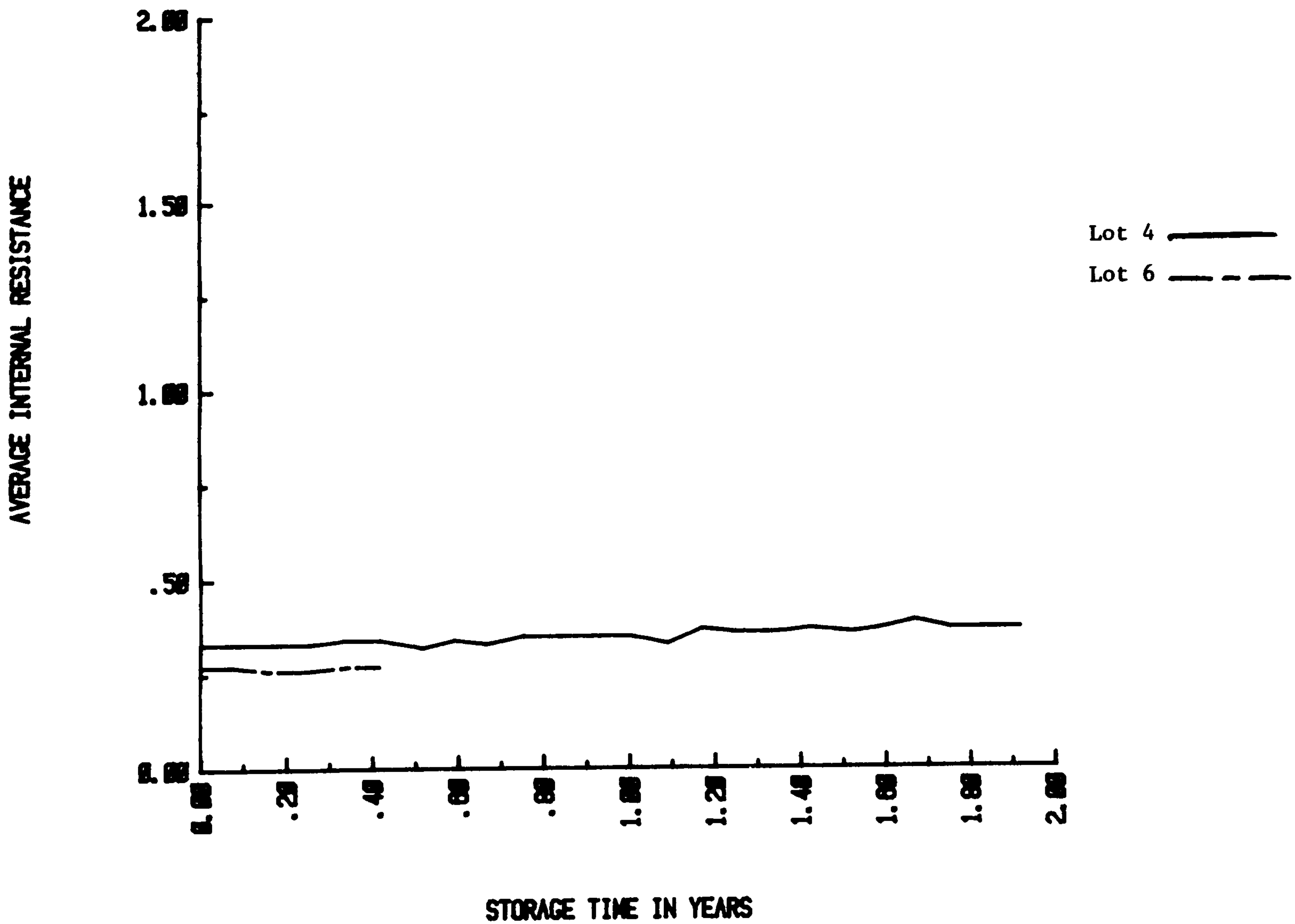

Figure 1. 20°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE RESISTANCE DATA IN OHMS

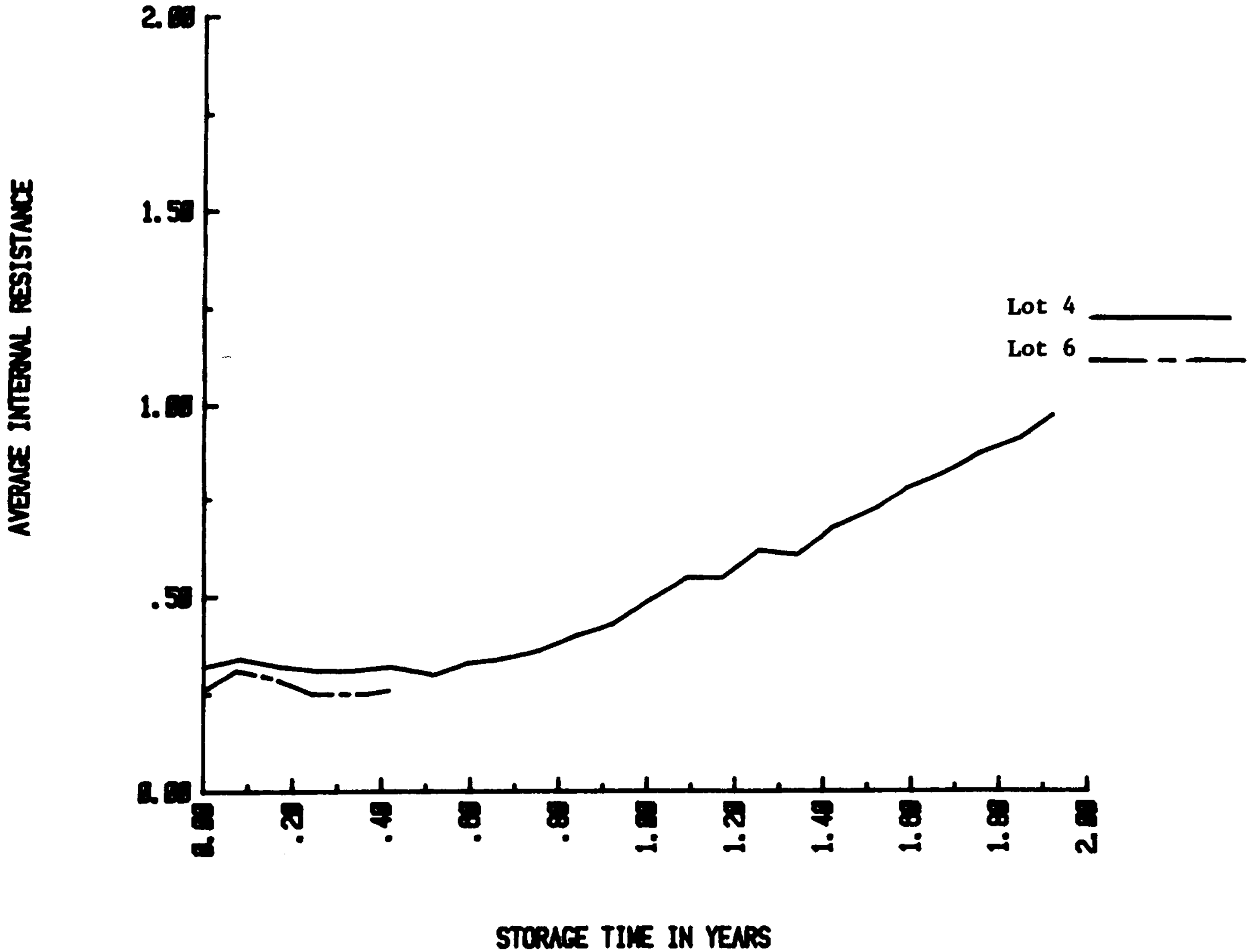

Figure 2. 50°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE RESISTANCE DATA IN OHMS

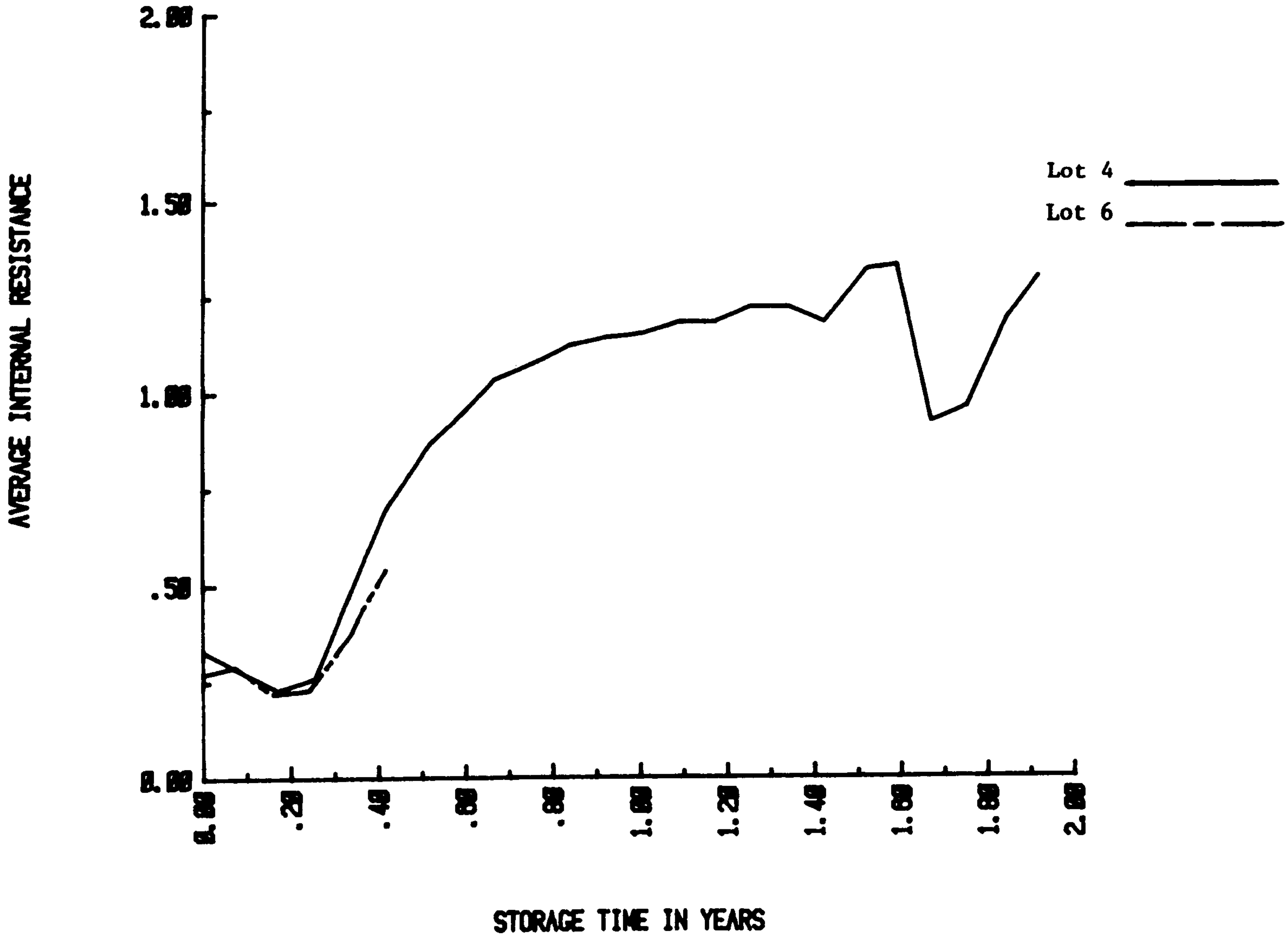

Figure 3. 60°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE RESISTANCE DATA IN OHMS

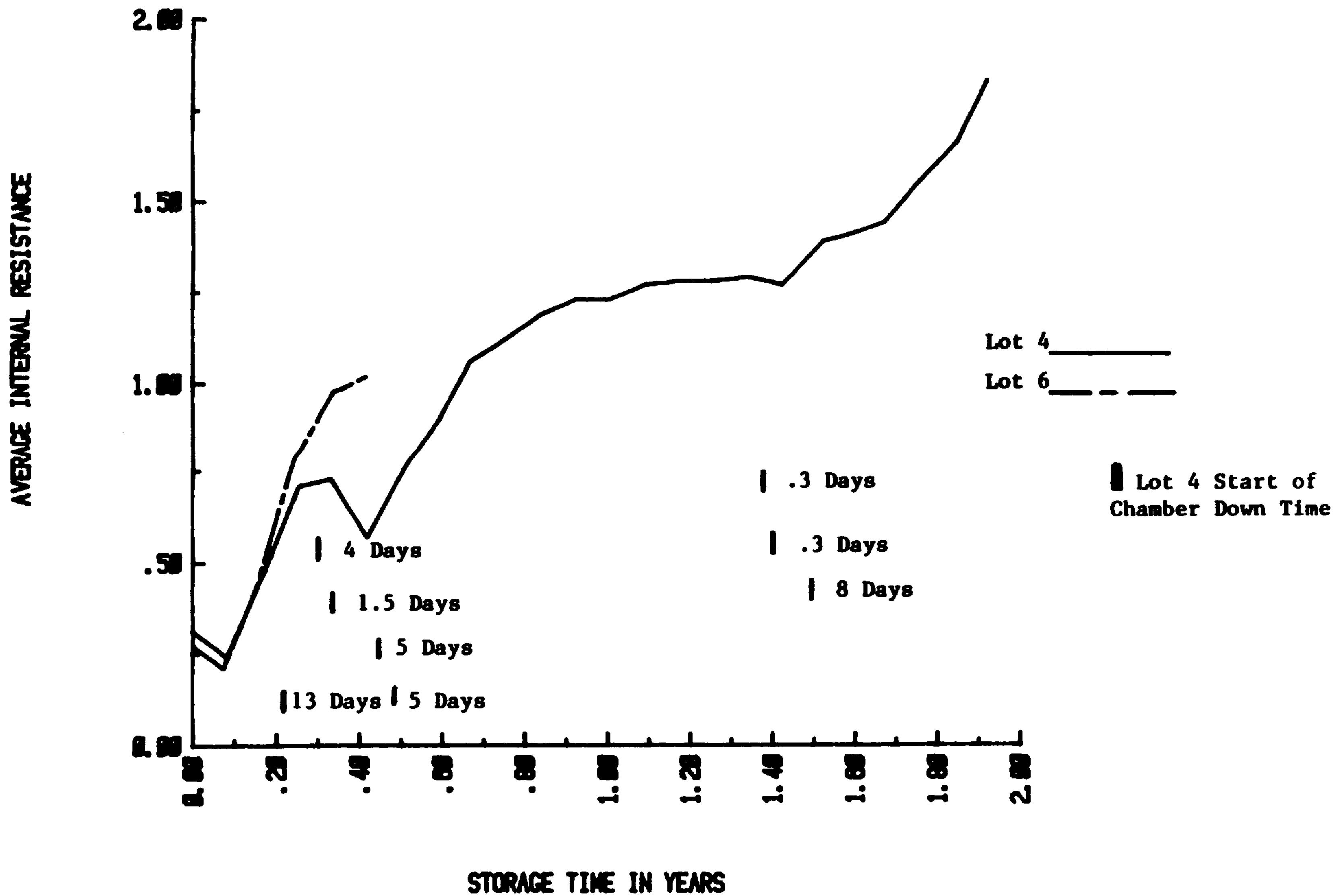

Figure 4. 70°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE RESISTANCE DATA IN OHMS

ORIGINAL PAGE IS OF POOR QUALITY

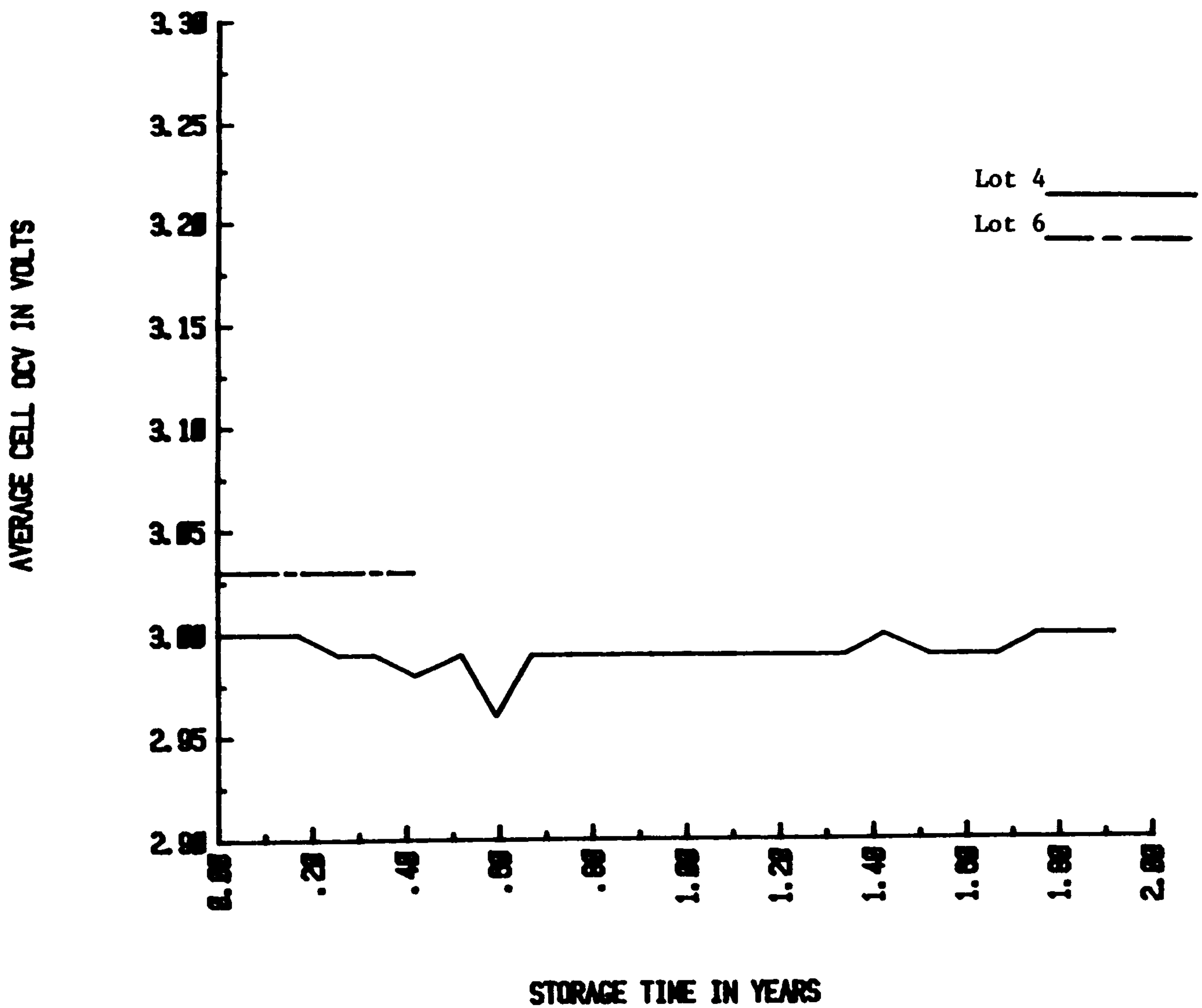

Figure 5. 20°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE OCV DATA

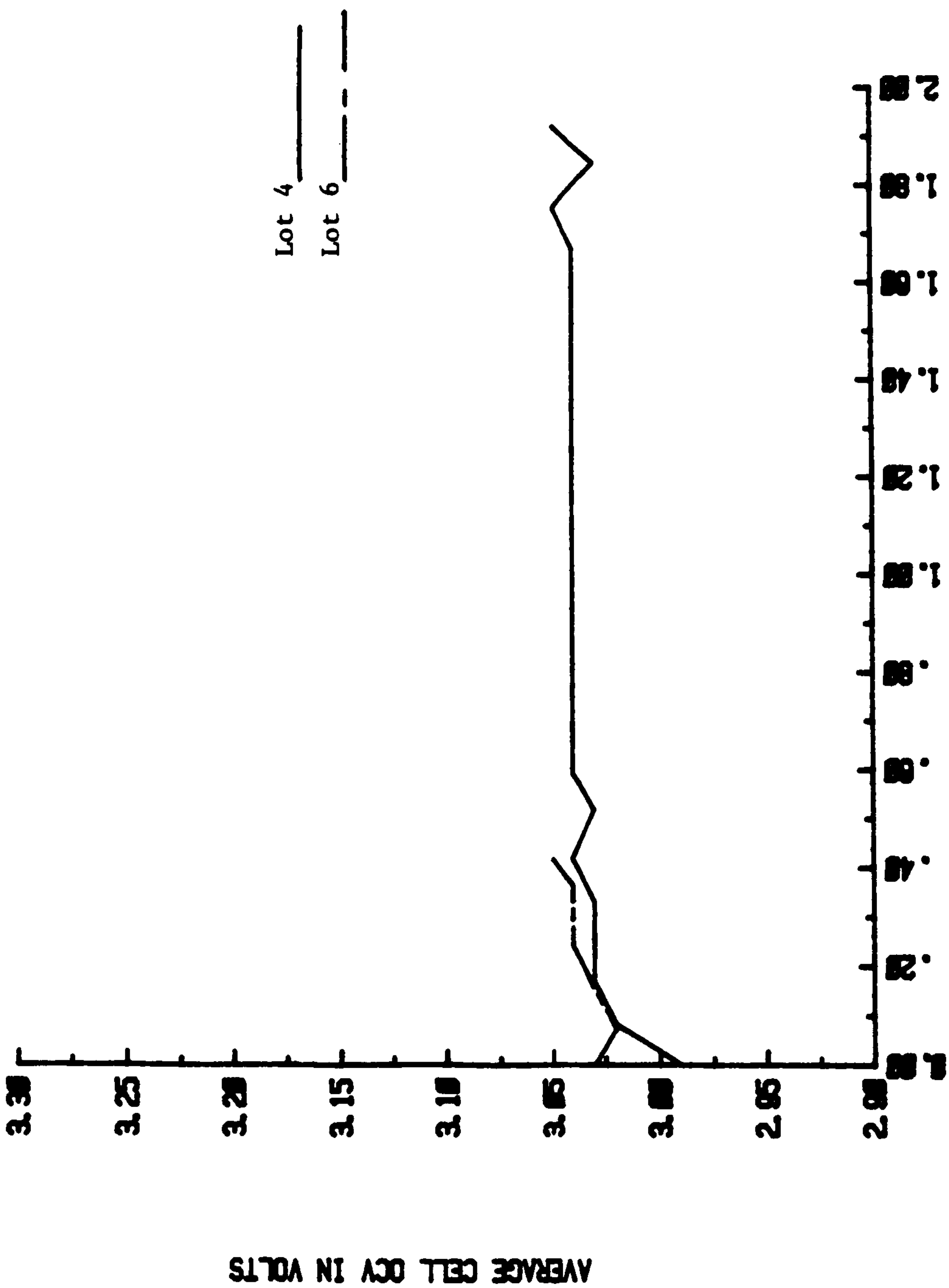

Figure 6. 50°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE OCV DATA

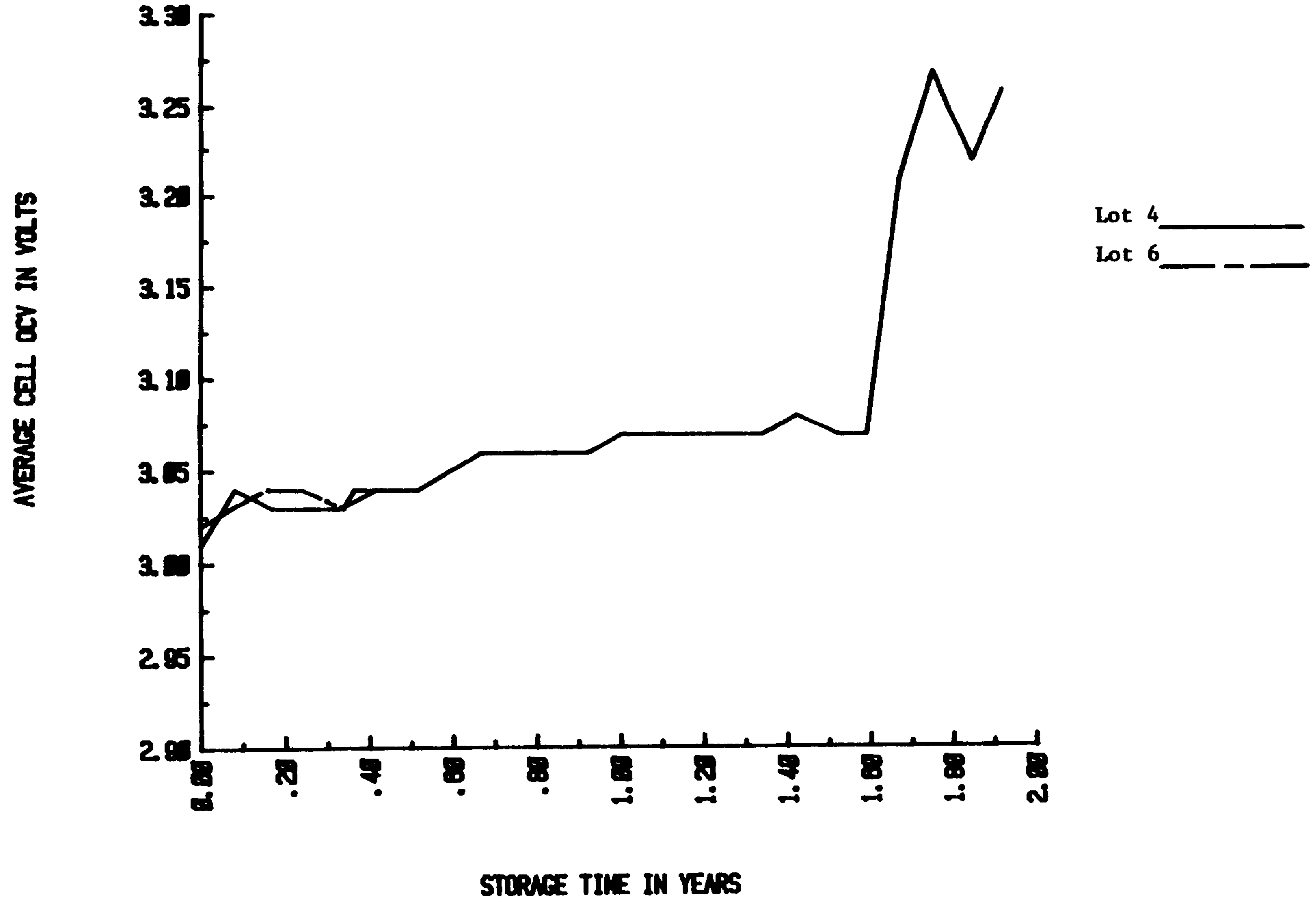

Figure 7. 60°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE OCV DATA

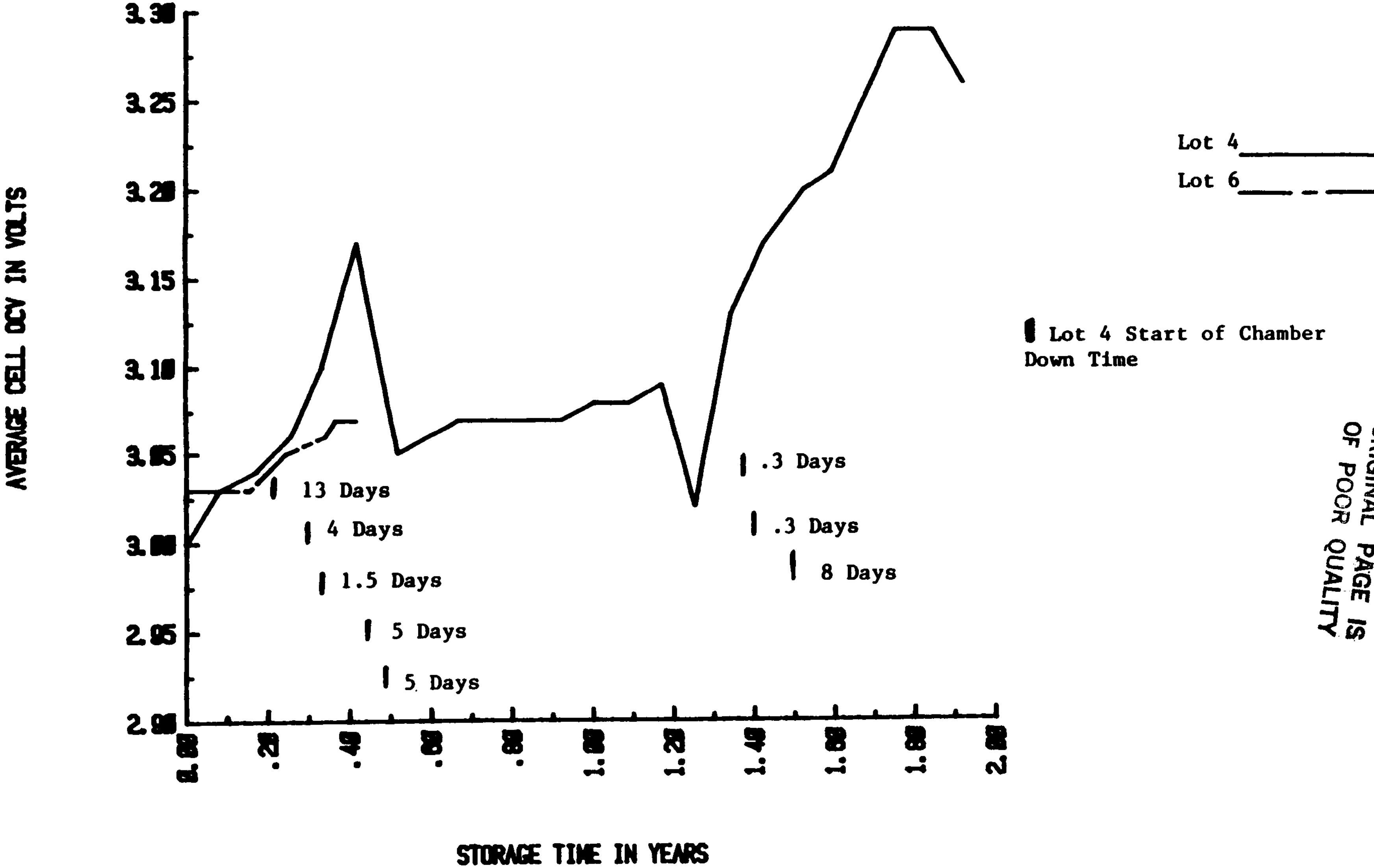

Figure 8. 70°C COMPARISON OF GALILEO LOT 4 & 6 CELL STORAGE OCV DATA

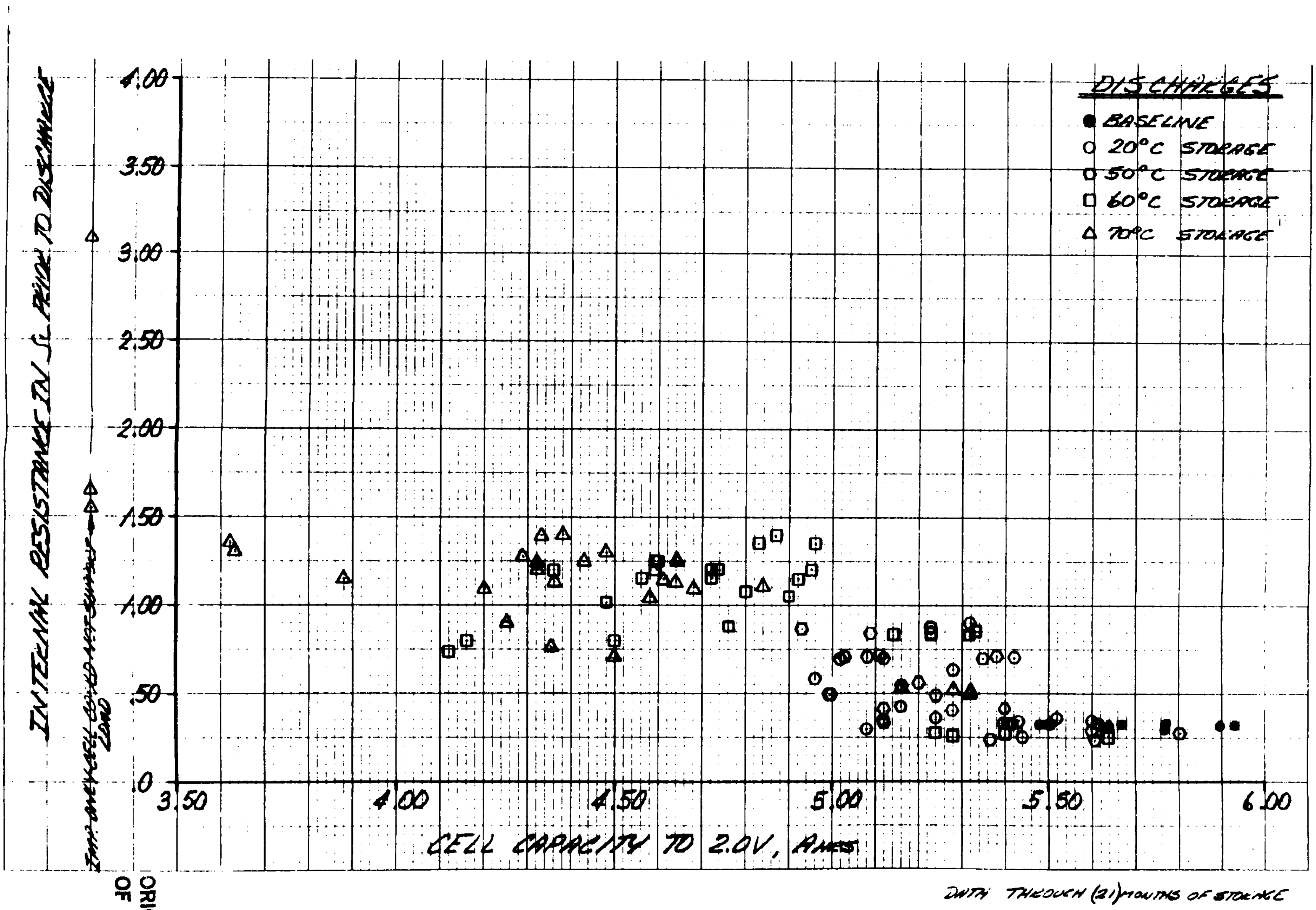

Figure 9. GALILEO LOT 4 COMPARISON OF STORED CELLS AT VARIED TEMPERATURES THEN DISCHARGED (GALILEO DISCHARGE—ALL CELLS AT 0°C, 4 AMPS CONSTANT CURRENT TO 2V CUTOFF)

TABLE 6. SINUSOIDAL VIBRATION INPUT QUALITY LEVELS

AXIS	FREQ, Hz	ACCELERATION, G (0 TO PEAK)	DISPLACEMENT, IN.
X	10 TO 30	–	0.24 (DOUBLE AMPLITUDE)
	30 TO 100	11.0	
	100 TO 170	2.0	
	170 TO 2000	1.0	
Y	10 TO 30	–	0.24 (DOUBLE AMPLITUDE)
	30 TO 70	11.0	
	70 TO 100	2.0	
	100 TO 2000	0.6	
Z	10 TO 46	–	0.047 (DOUBLE AMPLITUDE)
	46 TO 135	5.0	
	135 TO 200	3.0	
	200 TO 450	1.5	
	450 TO 2000	2.0	

NOTE: SWEEP RATE, ALL AXES, IS 2 OCT/MIN, ±10% ON AMPLITUDE.

TABLE 5. RANDOM VIBRATION INPUT QUALITY LEVELS

AXIS	FREQ, Hz	PSD, g^2/Hz	SLOPE, dB/OCT
[g(rms) = 11.54]	20 TO 35 Hz	—	+ 6
	35 TO 80	1.5	-
X	80 TO 215	-	-12.0
	215 TO 500	0.03	-
	500 TO 1000	—	-15.0
	1000 TO 2000	0.001	-
[g(rms) = 8.45]	20 TO 35		+6.0
	35 TO 60	1.5	
	60 TO 123		-21
Y	123 TO 400	0.01	
	400 TO 617		-16.0
	617 TO 2000	0.001	
[g(rms) = 9.05]	20 TO 120	0.1	-
Z	120 TO 150	—	+15.0
	150 TO 280	0.3	-
	280 TO 640	—	-15.0
	640 TO 2000	0.005	-

TABLE 6. DECELERATION AND SPINNING REQUIREMENTS

DESCENT DECELERATION

- Z-AXIS
- PEAK LOAD OF 425 G'S
- 300 G'S FOR 30 SEC
- 0.050 IN. MAX STATIC DEFLECTIVITY AT 425 G'S

SPINNING

RPM	TIME PERIOD
70	1 HR (LAUNCH)
3	30 DAYS (ON ORBITER)
10 TO 11	150 DAYS (ON PROBE)
0.25 TO 40	1 HR
0 TO 120	1 TO 2 MIN (DURING DESCENT; UP TO 425 G)
0	REMAINDER TO MISSION

TABLE 7. MISSION TEMPERATURE PROFILE
(prior to descent)

STEP	t, MONTHS	CUM t, MO	ACTIVITY	TEMP, °C
1	0	0	CELL ACTIVATION	–
2	2.0	2.0	MODULE FABRICATION	30 MAX
3	13.0	15.0	STORAGE DURING QUAL/ACCEPTANCE	0
4	0.5	15.5	SHIPMENT TO SPACECRAFT	30 MAX
5	2.0	17.5	INSTALLATION ON SPACECRAFT	30 MAX
6	0.5	18.0	SHIPMENT TO CAPE	40 MAX
7	4.0	22.0	PRELAUNCH TO CAPE	30 MAX
8	0.1	22.1	LAUNCH	60 MAX
9	19.0	41.1	INTERPLANETARY	20 MAX
10	5.0	46.1	COAST	0 NOMINAL

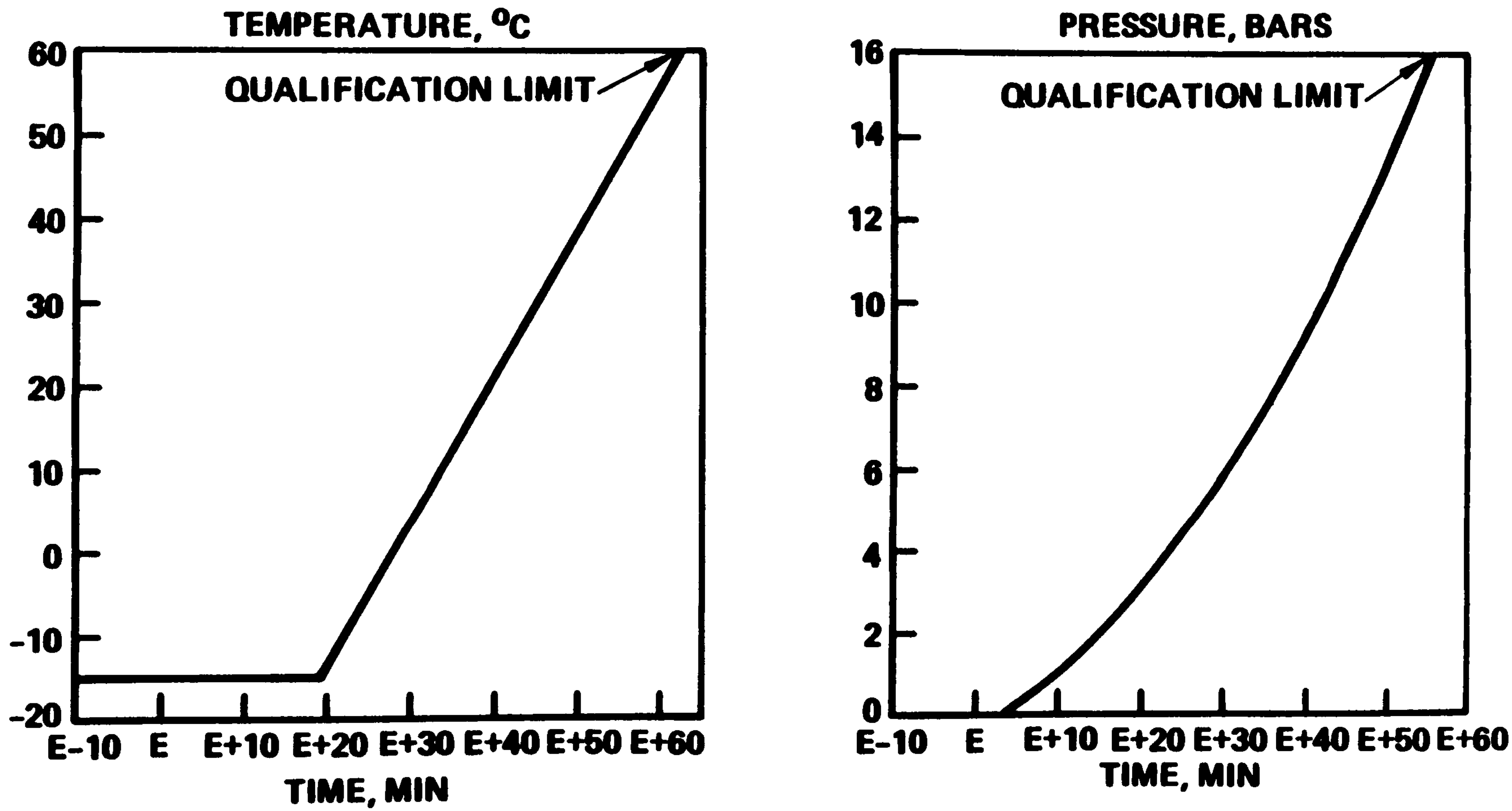

Figure 10. ENTRY TEMPERATURE/PRESSURE PROFILES